Acoustic Blind Deconvolution in Uncertain Shallow Ocean Environments

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LONG-TERM GOALS

The overall long-term goal for this project is to develop engineering tools that are useful to the Navy as it operates in uncertain, partially-known, or unknown ocean environments. During the last year, this project has focused on further determining the utility of a time-reversal-based technique for blind deconvolution of recorded sounds broadcast by a remote source with emphasis on determining if and how the results might be used for tracking and identification of remote sources in poorly known or unknown ocean waveguide environments.

The long term goals of this project since are: *i*) to determine the effectiveness of artificial time reversal (ATR) for the purposes of blind deconvolution in noisy unknown ocean sound channels, *ii*) to effectively apply ATR to marine mammal sounds recorded in the ocean with vertical and/or horizontal arrays, and *iii*) to utilize the ATR-corrected signals and ocean-sound-channel impulse response estimates to identify and track individual marine mammals (or other sound sources of interest).

OBJECTIVES

Since early 2009 this project has focused on developing an acoustic-ray-based version of artificial time reversal (ATR), a technique for recovering the original signal and the source-to-array impulse response for a remote unknown sound source in an unknown ocean waveguide [1,2]. The specific objectives are to: *a*) determine the signal-to-noise, array size, and array element number limitations of ATR via acoustic propagation simulations, *b*) verify these findings with simple airborne-sound laboratory experiments involving multiple microphones and several ray paths, *c*) obtain and process at-sea array recordings of remote-but-cooperative sound sources, and *d*) obtain and process marine mammal vocalizations for the purposes of marine mammal tracking and identification. This research effort extends the past mode-based version of ATR [1] to higher frequencies and smaller receiving arrays, and will identify its capabilities and limitations.

APPROACH

Over the last year, this project has exploited experimental results and simulations in approximately equal portions. The primary focus of the project has been to understand the capabilities and limitations of ATR when applied to the underwater propagation data measured during CAPEX09, an experiment conducted by Dr. Daniel Rouseff and collaborators at the University of Washington - Applied Physics

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Laboratory (UW-APL) in 60 m of water in Lake Washington, just west of Seattle. In this experiment chirp signals with a bandwidth of 1.5 kHz to 4.0 kHz were broadcast from a depth of 30 m and recorded by a 7-m-long 32-element receiving array at source-array ranges of 100 m, 250 m, and 500 m. This experiment represents an ideal test bed for ray-based ATR because the environment is relatively simple, the number of array elements used in the processing may be varied over a wide range, and because the ATR results are excellent at the shortest range and decrease in quality with increasing range. Thus, the fundamental limitations of ATR may be deduced from this data set.

Propagation simulations in a comparable but simplified environment out to a range of 1 km have been conducted with the modal-sum propagation model KRAKEN, and the ray-propagation code Bellhop. Here, simulated broadband Gaussian distributed noise has been added to both the actual and the simulated signals to study the influence of signal-to-noise ratio (SNR) on ATR results.

These ATR investigations involving CAPEX09 and underwater sound simulations are the current doctoral research of Ms. Shima H. Abadi, who should advance to candidacy before the end of the calendar year.

In addition, an undergraduate has been hired to construct a simple three-dimensional airborne sound experiment to test ATR concepts with planar arrays of inexpensive microphones.

WORK COMPLETED

The ATR technique uses measured signals from a known array of receiving phones to separately estimate the original source signal and the source-to-array-element transfer functions from an unknown remote source in an unknown multipath environment. In this investigation of ray-based ATR, the estimated source signal and transfer functions are time shifted by the (unknown) propagation delay along a reference ray found from plane-wave beamforming of the measured signals. In addition, the ATR-estimated source signal and transfer functions are normalized as part of the ATR processing so an overall amplitude scaling is also unknown. However, when ATR performs well, the estimated source-signal waveform and the transfer-function waveforms are accurately recovered.

The work completed in the past year has involved determining how the operational parameters (number of receivers, signal-to-noise ratio, number of identifiable paths, source-array range, etc.) influence ATR performance for signals having frequencies in the 1.5 to 4.0 kHz range. Here the primary performance parameter for original-source-signal reconstruction has been the cross correlation coefficient between the original and ATR-reconstructed signals. In addition, a simple and robust means of using the ATR-estimated transfer functions for remote unknown source localization has been developed. (And, for completeness, the last publication [3] from the past acoustic uncertainty portion of this research project has been conditionally accepted for publication in the Journal of the Acoustical Society of America.)

RESULTS

To date, this investigation effort has determined the following about the ATR-estimated source-signal waveform using the CAPEX09 data set. (*i*) The cross-correlation coefficient with the original signal may be at or above 98% when the SNR is above 5 dB, and at or above 92% when the SNR is as low as 0 dB when all 32 receiving phones are used. (*ii*) The cross-correlation coefficient with the original signal may be above 98% when 6 to 8 receivers are used, and above 90% when as few as 3-4 receivers are used. (*iii*) A coherent combination of ATR results using different reference rays generally leads to

an improved cross-correlation coefficient with the original signal when the individual-ray ATR results are comparable.

To date, this investigation effort has determined that the ATR-estimated transfer functions can be used to robustly estimate the source-array range and source depth in a multipath environment when the water column depth and speed of sound profile are known at the receiving array location. As mentioned above, the ATR-estimated transfer functions do not recover the propagation time from the source to the array, but they do provide the arrival time differences for the various ray paths that reach the array. When the received ray-path angles for the various arrivals are known from beamforming, the ray-arrival timing and ray-angle information may be combined with a ray-propagation code to estimate the source range and depth. The idea is as follows. First, the ray code and the environmental information at the array are used to compute ray paths, launched at the appropriate angles, that start at the array and proceed out to the largest range of interest, assuming a range-independent environment. The ATR transfer-function results and the known beamformer output are sufficient to perform a simple time-reversal calculation along these few ray paths. In the present effort, impulses are launched along each ray at the appropriate time, and allowed to propagate away from the array. This creates a small swarm (or cloud) of impulse-markers – one traveling along each ray path – that should converge on the source location at the same time, if everything is perfect. Unfortunately, the inevitable environmental mismatch and relative timing errors prevent a perfect convergence. However, the average and the standard deviation of the impulse marker locations can be monitored, so an estimate of the unknown source's location can be obtained from the average marker location when the marker cloud is the smallest, that is, when the standard deviation of marker position is a minimum.

The results of such a calculation are shown on Figure 1, where the standard deviation of marker position is plotted as a function of range from the receiving array. Here the actual source-array range is 100 m, and a distinct minimum in the marker-location standard deviation occurs at a range of 102 m. The impulse-marker average depth at this range is 28 m, which is also within 2 meters of the actual source depth. Thus, the relative timing information in the ATR-estimated transfer functions can be used to successfully localize the source when some environmental information is known at the array and a ray-propagation code is available.

For comparison, the same experimental signals were used to perform incoherent and coherent Bartlett matched field processing (MFP) assuming (again) a range-independent environment identical to that found at the array. The incoherent results, a combination of harmonic MFP results at six frequencies (1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 kHz), are shown on Figure 2. The inevitable actual-vs.-model environmental mismatch leads to a ridge in the ambiguity surface that is concentrated along the most-direct ray path between the source and the array. In this case, two peaks occur in the vicinity of the source at ranges of 90 m and 110 m at a depth of 25 m. Neither is more accurate than the simple ray-trace results even though the computational effort to produce Figure 2 was substantially greater than that necessary to produce Figure 1.
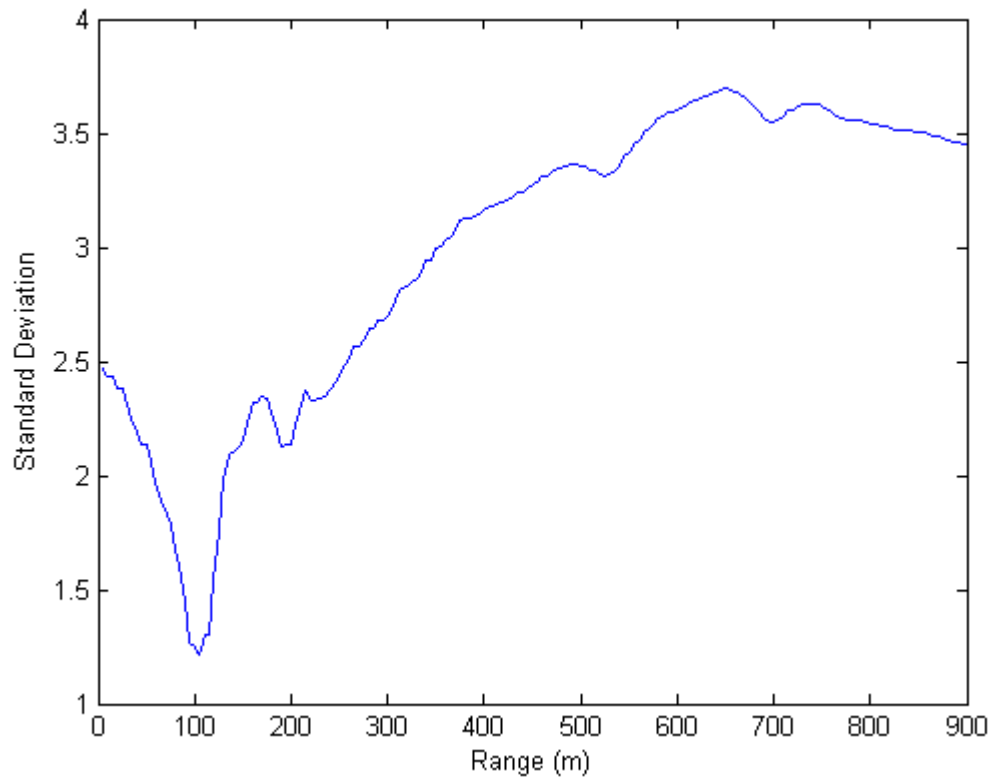
***Figure 1. Standard deviation of impulse-marker locations vs. array-source range.
The array lies at zero range. The minimum of the standard deviation indicates the most
likely range between the source and the array. Here, there is one clear unambiguous
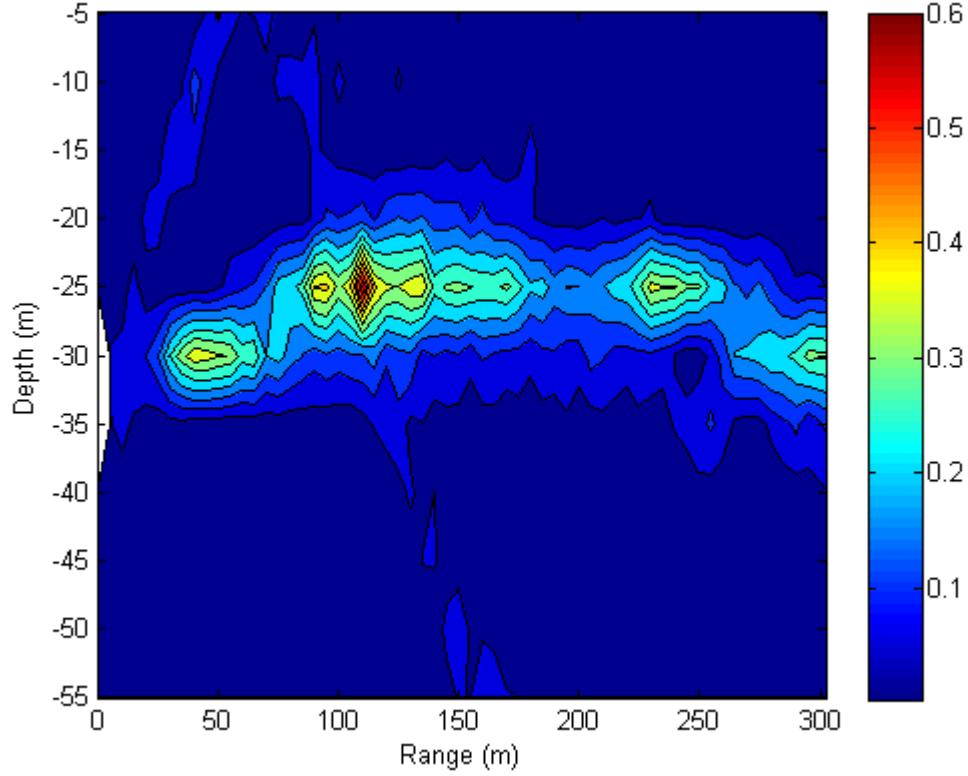minimum out to a range of 900 m.***

Figure 2. Incoherent Bartlett Matched Field Processing (MFP) ambiguity surface for the same experimental data used to produce Figure 1. Here, the ray-based propagation code Bellhop was used, and harmonic MFP results from 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 kHz were combined. The actual source was located at a range of 100 m and a depth of 30 m. Here, two peaks occur in this vicinity at ranges of 90 m and 110 m at a depth of 25 m.

Coherent Bartlett MFP results for the same experimental data are shown on Figure 3. Here the ambiguity surface is determined as the magnitude of the cross correlation function of the ATR-estimated impulse response and an impulse response calculated for the 1.5 kHz to 4.0 kHz signal bandwidth. Here again, the inevitable actual-vs.-model environmental mismatch leads to an ambiguity-surface ridge that is concentrated along the most-direct ray path between the source and the array. Although these results are comparable to those shown in Fig. 2, the highest ambiguity-surface peak occurs at a range of 250 m and a depth of 26 m. The peak closest to the actual source location is at a range of 125 m and a depth of 24 m. Again, neither is more accurate than the simple ray-trace results even though the computational effort to produce Figure 3 was substantially greater than that necessary to produce Figure 2.

Therefore, for this simple test case, the simplest source localization approach performs best. Additional assessments of this type must be made to determine if this finding is a genuine trend.
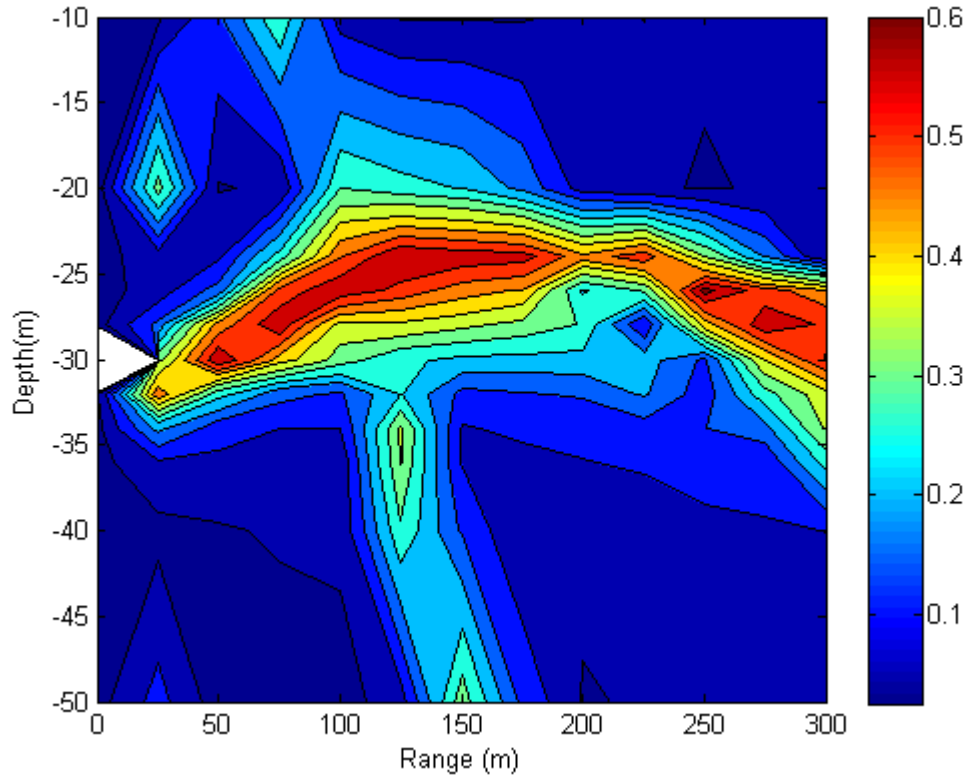
Figure 3. Coherent Bartlett Matched Field Processing (MFP) ambiguity surface for the same experimental data used to produce Figure 1. Here again, the ray-based propagation code Bellhop was used, and the ambiguity surface is the absolute value of the cross-correlation coefficient between the ATR-estimated and calculated impulse responses. The actual source was located at a range of 100 m and a depth of 30 m. Here, the highest ambiguity-surface peak occurs at a range of 250 m and a depth of 26 m. The peak closest to the actual source location is at a range of 125 m and a depth of 24 m. Thus, a single distinct source localization result is not obtained.

IMPACT/APPLICATION

In broad terms, this project ultimately seeks to determine what is possible for a sonar system when the available environmental information is uncertain, incomplete, or unknown. The capabilities of future Naval sonar systems will be enhanced when sonar techniques are developed that do not rely on detailed knowledge of the acoustic environment. Thus, this research effort on determining the effectiveness and utility of ray-based artificial time reversal, a relatively-new blind deconvolution scheme, may eventually impact how transducer (array) measurements are processed for detection, localization, tracking, and identification of remote unknown sound sources.

TRANSITIONS

The results of this research effort should aid in the design of sonar signal processors for tactical decision aids. However, at this time no direct transition links have been established with more applied research programs. Once the current results are more firmly established and validated, a transition path through NRL or one of the Navy's Warfare Centers will be sought.

RELATED PROJECTS

This project is currently using acoustic array recordings of known man-made sounds made available by Dr. Daniel Rouseff of the UW-APL from the CAPEX09 experiment. And, more recently, Dr. Aaron Thode of SIO has provided acoustic array data collected in the arctic that includes man-made and marine mammal sounds. Dr. H.-C. Song of SIO has also used artificial time reversal for processing underwater communication sequences.

REFERENCES AND PUBLICATIONS

[1]   Sabra, K.G., and Dowling, D.R. (2004), "Blind deconvolution in ocean waveguides using artificial time reversal," *Journal of the Acoustical Society of America*, Vol. 116, 262-271.

[2]   Sabra, K.G., Song, H.-C., and Dowling, D.R. 2010 "Ray-based blind deconvolution in ocean sound channels," *Journal of the Acoustical Society of America – Express Letters*, Vol. 127, EL42-EL47.

[3]   James, K.R. and Dowling, D.R. "Pekeris waveguide comparisons of methods for predicting acoustic field amplitude uncertainty caused by a spatially-uniform environmental uncertainty," conditionally accepted for publication in *Journal of the Acoustical Society of America*. September 2010.

HONORS AND AWARDS

Ms. Shima H. Abadi won the Underwater Sound Student Presentation award at the 158th ASA Meeting in San Antonio, Texas, October 2009. Prof. Dowling was elected Fellow of the American Society of Mechanical Engineers, July 2010.